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TO: Dr. D. Mills
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TRITIUM-DOPED PHOTOVOLTAIC CELLS: PERFORMANCE ENHANCEMENT IN SILICON SOLAR CELLS

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Preliminary work with the University of Toronto on tritium-pumped solar cells confirms enhancement of the conversion efficiency under dark cell conditions. The experiment, using an electron beam to simulate tritium loading, shows that unilluminated silicon cell output powers are proportional to the beam accelerating voltage up to 30 KeV, covering the tritium beta radiation range. In contrast to a typical efficiency of 10% for photoirradiated silicon solar cells, these results indicate a potential efficiency of about 16% for a tritium-doped solar cells, an enhancement of 60%.

1. Introduction

In order to meet the projected future energy demands in the province, it is imperative that Ontario Hydro investigate all alternative and supplementary energy supply options [1]. Among these options, photovoltaic (PV) solar technology, while not presently practical for large-scale electricity generation, may have specialized applications in Ontario. PV systems may play a supplementary role, for example, in remote communities in Northern Ontario which are fuelled primarily by expensive diesel generation. To this end, the Science Section has been examining the feasibility of novel techniques to enhance the performance of PV solar cells.

The proposed scheme for PV performance enhancement described in this report is tritium doping of conventional solar cells. Preliminary calculations [2, 3] suggest that the tritium beta radiation could increase the effective PV efficiency, indicating the potential to yield cheaper solar power than is possible using conventional PV cells. Furthermore, tritium is primarily a by-product of Ontario Hydro's nuclear generation process. Here, this nuclear by-product is transformed into the key ingredient of a novel energy resource. This report details recent experimental work in collaboration with the University of Toronto's Department of Metallurgy and Materials Science investigating the influence of simulated tritium doping on solar cell performance.

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2. Technical Background and Recent Results

Two key processes are responsible for PV device operation. Firstly, an excess of carriers is created in the device by incident photons through electron-hole pair production. Secondly, these excess carriers diffuse and separate at a semiconductor junction, giving rise to a current flow in an external circuit.

Among the many factors limiting the conversion efficiency of PV cells is carrier recombination at the junction interface [4, 5]. It was initially postulated [2] that the introduction of tritium, a beta emitter, near the junction could create a biased field to minimize this process, increasing efficiency. Further refinements of this concept led to the idea that the tritium diffused into the PV structure adds an additional non-photogenerated current source term to the cell, resulting in increased output power.

Recent experimental work in collaboration with the University of Toronto has confirmed the above hypothesized enhancement of PV performance under tritium doping. Details of the research are given in Appendix 1. A summary of the work follows:

(1) A theoretical model for tritiated solar cells was developed. One result of the model is that, since the tritium beta energy is larger than the electron-hole pair production energy, the tritium contribution to the current has a gain factor greater than unity. The model thus predicts significant increases in cell efficiency under tritium loading.

(2) After an extensive literature review, a radiation hardened Si solar cell used for space research was chosen as the material for the feasibility study, based on cost, efficiency, and radiation resistance.

(3) A tailored electron beam facility was used to simulate tritium beta radiation. An electron microscope was modified for this purpose, and calibrated by comparing the simulator-pumped cathodoluminescence (CL) to an actual tritium gas-pumped CL standard.

(4) Building on the above, experiments were conducted under dark cell conditions (no solar illumination) using simulated tritium pumping of a Si solar cell, with electron energies in the range from 0 to 30 KeV.

(5) The experimental results indicate a possible power conversion efficiency of about 16% for a tritium-doped PV cell. In contrast, the power conversion efficiency for a typical photoirradiated Si solar cell is 10%. Tritium loading thus has the potential for a 60% increase in Si cell efficiencies.

3. Recommendations

The next logical stage in the development of tritium-doped PV technology is to confirm the predicted enhancement under solar illumination. Ongoing work at the University of Toronto includes characterization and calibration of a solar simulator system for this purpose. The solar simulator, recently acquired by the Science Section, consists of a 150 W Xe lamp and associated conditioning optics. Preliminary experiments will include comparative measurements of Si solar cell performance under one sun illumination with and without simulated tritium loading.

Subsequently, the experiment should extend the above measurements to PV materials other than Si. Although no significant radiation damage was found over the duration of the experiments in the radiation hardened Si cells used, degradation is expected to occur over longer periods of time. This will tend to lower the usable lifetime of these materials. This effect precludes the use of some promising high-efficiency materials such as GaAs, which are unfortunately very highly susceptible to radiation damage. A good compromise between high efficiency and radiation resistance may be found in GaP and InP. These latter materials may be grown to specification at the University of Toronto's high-purity liquid phase epitaxy (LPE) growth system.

Assuming the above stages are successful, demonstration type tritium-doped PV solar cells may then be fabricated. At this stage, tritium doping concentrations should be tested, to establish optimum lifetime and efficiency levels for these devices. Careful characterization should then determine the appropriateness of the enhanced PV cells for use in specialized applications.

The conversion of the tritium beta emission energy to electrical energy via a semiconductor junction device - the zero illumination situation described in this report - also leads to the possibility of a low power nuclear battery [6]. Should the concept be proven to be technically and economically feasible, very large-scale integrated (VLSI) chips could be doped with tritium so that they carry their own power source. New Business Ventures Division will be contacted for such business opportunities.

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Appendix 1.

Ontario Hydro Research Division
Contract PO #11-58214-11/ RN# 0863-1435
Progress Report 1991

Enhancement of Solar Cell Performance by Simulated Tritium Doping

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1. Overview

The hypothesis under test is that the performance of photovoltaic devices may be enhanced by using simulated tritium doping. The aim of the work proposed under this contract was to test this hypothesis. The results of the work performed to date confirm the hypothesis and indicate that significant improvements in solar cell performance can be achieved using simulated tritium doping.

2. Progress Towards Achieving Milestones and Objectives

The primary objective of this research study was to investigate the feasibility of enhancing the performance of solar photovoltaic (PV) devices using simulated tritium doping. The milestones that we planned for completion under this contract were:

(1) Completion of a literature review.
(2) Development of a model for a tritium enhanced solar cell.
(3) Testing of prototype cells.
(4) Establishment of a tritium simulator.
(5) Preparation of a final report on the program.

We are happy to be in a position to report that we have now completed all phases of the program and have satisfied all of the milestones that we set out to accomplish. In the course of this

research, new and exciting results were forthcoming. As a result of these developments, we have formulated a proposal for future research work.

3. Summary of Progress to Date

(1) An exhaustive literature review was instigated and has resulted in a collection of over 500 papers and articles. These references were compiled by performing a computer search, and by following papers referenced in other works. We collected material in seven areas. Namely in materials, in array and structure technologies, in design and modelling of performance of solar cells, in the area of radiation damage, in the area of solar cells and applications relating to space, in new developments and progress, and in a miscellaneous category. These papers generally cover a period from about six years ago to date. Several key findings of our literature review include:

(a) Electron beam irradiation studies have been performed on cells fabricated from Si, GaAs, GaAlAs, GaP, InGaP and InP material systems. Marked differences in radiation resistance have been found between the different types of cell. The Si-based cells were by far the poorest, with typical radiation damage thresholds for 1 MeV irradiation of about 10^{12} e/cm^2 compared with GaP-based cells exhibiting the most stable behaviour, with thresholds exceeding 10^{15} e/cm^2 under similar conditions. Similar results were found for proton-irradiated cells.

(b) The choice of materials for high efficiency solar cells has been a continuing debate which has been a compromise between cost favouring Si and performance. In terms of performance in the absence of coincident irradiation, the basic materials parameters limiting efficiencies are well recognised. These include bandgap of the primary cell, or bandgap combinations for multijunction cells, as well as minority carrier properties such as diffusion lengths and lifetimes.

The Solar Energy Research Institute (SERI) have been concentrating on InP and GaP-based cells as well as GaAs-based cells. Varian, on the other hand, have focused their efforts on AlGaAs and InGaAs cells. Chevron are currently working on GaAsP cells whilst SPIRE Corporation are researching GaAsP and InP on Si cells. Currently efficiencies for these cells in excess of 35% have been reported, comparing sharply with state of the art Si-based cells having efficiencies below 20%. Tandem multijunction cells operating under super unity sun operation have also been reported with efficiencies above 40%. It is worth mentioning that commercial III-V solar cells having efficiencies in excess of 20% are rare.

(c) Noteworthy new developments in cell technology include a recent disclosure by Texas Instruments of poycrystalline Si microsphere based solar cells. However, although this technology promises cheaper solar energy, the interior efficiencies

of these cells even when compared with conventional state-of-the-art single crystal Si cells makes them unlikely candidates for study at the present juncture. Indeed, the poor radiation hardness of this material is an additional consideration that further limits the potential of this type of cell as regards exploitation for tritium-enhanced solar cell development.

(2) A model for a tritiated solar cell was developed in this program. The basic features of the model were to supplement the standard photogenerated current term in the solar cell equation with a similar form of current term relating to the tritium beta flux. Of note here is that the standard photogenerated current is linear in the photon flux owing to the correspondence between photon incidence and electron-hole pair creation. The case for tritium irradiation is distinct in that each incident beta particle having mean incident energy in the 5 KeV range is able to create an abundance of electron-hole pairs (as the pair production energy is of the order of a few eV per pair). The tritium "photocurrent" term, therefore, has a gain factor of greater than unity. The standard gain factor for a 1 sun solar cell would have a unity gain factor. Our simple model is, therefore, able to predict significant increases in cell efficiency due to this additional non-linear term. These findings were confirmed by our tritium simulation experiments, which will be discussed shortly.

Figure 1 shows the results of our theoretical calculations for the influence of tritium beta radiation on cell performance (output power), for a cell illuminated under various photon fluxes. The percentage increase in output power given on the y-axis of this graph relates to the power gain for a cell irradiated with and without 1 atm. of tritium gas. A gain coefficient of 4 for electron-hole pair production (corresponding to Si) was assumed in these calculations. A cell reverse leakage current of 1 nA and an operating temperature of 300 K was also assumed.

Clearly, when no light impinges on the solar cell the output power is totally dictated by the tritium induced electron-hole pair production. On the other hand as the illumination intensity is increased, an increased contribution from the photogenerated flux is expected, and is evident from Figure 1. Trickle powers (unilluminated cell conditions) of the order of a few mW are calculated, and contrast with typical photogenerated powers of about 5-10 mW under normal operating conditions. These numbers assume conversion efficiencies typical of standard commercial Si solar cells, and would naturally increase when resorting to more efficient state of the art solar cells.

(3) A number of candidate cell materials were identified which would satisfy two main criteria. Firstly, to provide a reasonable cell efficiency under normal solar irradiation, and secondly, to have an ability to withstand the adverse effects of long term exposure to a flux of high energy particles. The latter criteria drew us naturally to certain materials that had been developed for radiation hard space solar cells. Although this criteria generally tended to favour the wider bandgap materials, especially InP and GaP-based solar cells, certain Si cells have been developed

for space cells with reasonable efficiencies and most importantly at low relative cost. On the other hand, although GaAs-based cells have shown great terrestrial promise as candidates for high efficiency solar cells, the problems of readily succumbing to radiation damage precluded these materials as candidates. It was for this reason that our initial studies concentrated on readily available, reasonably efficient, cheap Si space solar cells. It was these structures that were the focus of the subsequently reported work. In the next phase of this recent program we are planning to investigate GaP-based cells which we will grow to specification in our custom high purity liquid phase epitaxy (LPE) growth system.

(4) A key part of this research program was to establish a tritium simulator to have the flexibility to mimic the well-documented characteristics of tritium beta radiation. To this end a Hitachi S-320 electron microscope was modified to provide this facility. The beam energy and flux could be adjusted to provide a wide range of electron flux and simulate the real beta distribution. Indeed, we carefully calibrated the system by measuring the beam flux at a given energy. This was accomplished by directing the electron beam through a pinhole aperture into a Wehnault cylindrical analyzer and measuring the beam current to ground with a Keithley electrometer having fA resolution. Because of our ability to adjust the objective aperture over a wide range, we were able to access a wide range of incident electron fluxes. In a separate set of experiments on cathodoluminescence (CL) we have been able to compare tritium gas pumped luminous intensities with those from a similar simulated tritium experiment using CL, and thus were able to empirically calibrate integrated simulated tritium experiments with an actual tritium gas standard experiment. We, therefore, have now established a fully calibrated tritium simulator.

(5) The characteristics of a number of cells were measured in our calibrated tritium simulator. The major findings of this research program, however, can best be illustrated by the results given in the Figures. These results are for a standard space enhanced Si solar cell at room temperature. The solar cell output power was established by integrating the power quadrant current-voltage characteristic of the cell under each irradiation condition. Interestingly, the fill factor for these cells was very high, approaching about 90%, and, therefore, a reasonable approximation to the cell output was given by the product of the open circuit voltage and the short circuit current of the cell. In order to establish a power conversion efficiency, it was necessary to establish the beam current incident on the cell. This was achieved as discussed above, together with a similar measurement of the sample current to ground. The close agreement between these numbers indicated that only an almost insignificant fraction of the electrons incident on the cell were reflected from it over the range of electron energies investigated. A noticeable deviation was only apparent over 30 KeV. Incident electron beam power was, therefore, given by the product of the incident electron voltage and the incident beam current. The ratio of the cell output power to incident beam power was taken as a measure of the power conversion efficiency of the cell under simulated tritium irradiation. These results are given in Figures 2 and 3.

Fig. 2 gives an overview of the efficiency over the range of electron energies from 0 to 30 KeV,

while Fig. 3 gives a detail of the dependence over the range 0 to 20 KeV, the tritium range. Key points to note are the relatively rapid increase in cell efficiency with increasing beam voltage, and the remarkable power efficiency values. Indeed, if the spectra are corrected for the actual tritium distribution function and are integrated out, then an effective power conversion efficiency of about 5-6% is derived. Given that this dependence is for a dark cell condition, and taking into account firstly the additive nature of the efficiency contribution as follows from the discussions above, and secondly the typical power conversion efficiencies of about 10% for a typical photo-irradiated Si solar cell, then these results predict a possible power conversion efficiency of about 15-16% for a tritium doped PV cell. This remarkable augmentation of the efficiency resulting from tritium irradiation has been instrumental in dictating our future research plans in this area.

4. Outline of Next Stage

The primary objective of the next phase of the proposed research program is to continue to pursue the research into the development of a tritium enhanced PV cell as a result of the exciting and encouraging results of our initial feasibility study with simulated tritium doping. The initial feasibility study directly showed how simulated tritium doping could be effective in increasing the efficiency of a typical solar cell performance from about 10% to about 15%. A clear message of this research then is that detailed research into structures and materials should be undertaken, together with tests using simulated tritium testing under solar illumination conditions, and finally experiments utilizing real (rather than simulated) tritium loading. The proposed research program is, therefore, designed to address these requirements and is organized to have six milestones associated with achieving these goals. The milestones are as follows:

(1) Identification of suitable test structures.
(2) Fabrication of selected test structures.
(3) Characterization of selected materials and structures.
(4) Performance of selected structures under simulated tritium irradiation.
(5) Performance of selected structures under solar illumination conditions, utilizing simulated tritium irradiation.
(6) Performance of selected structures under actual tritium irradiation.
(7) Preparation of a final report.

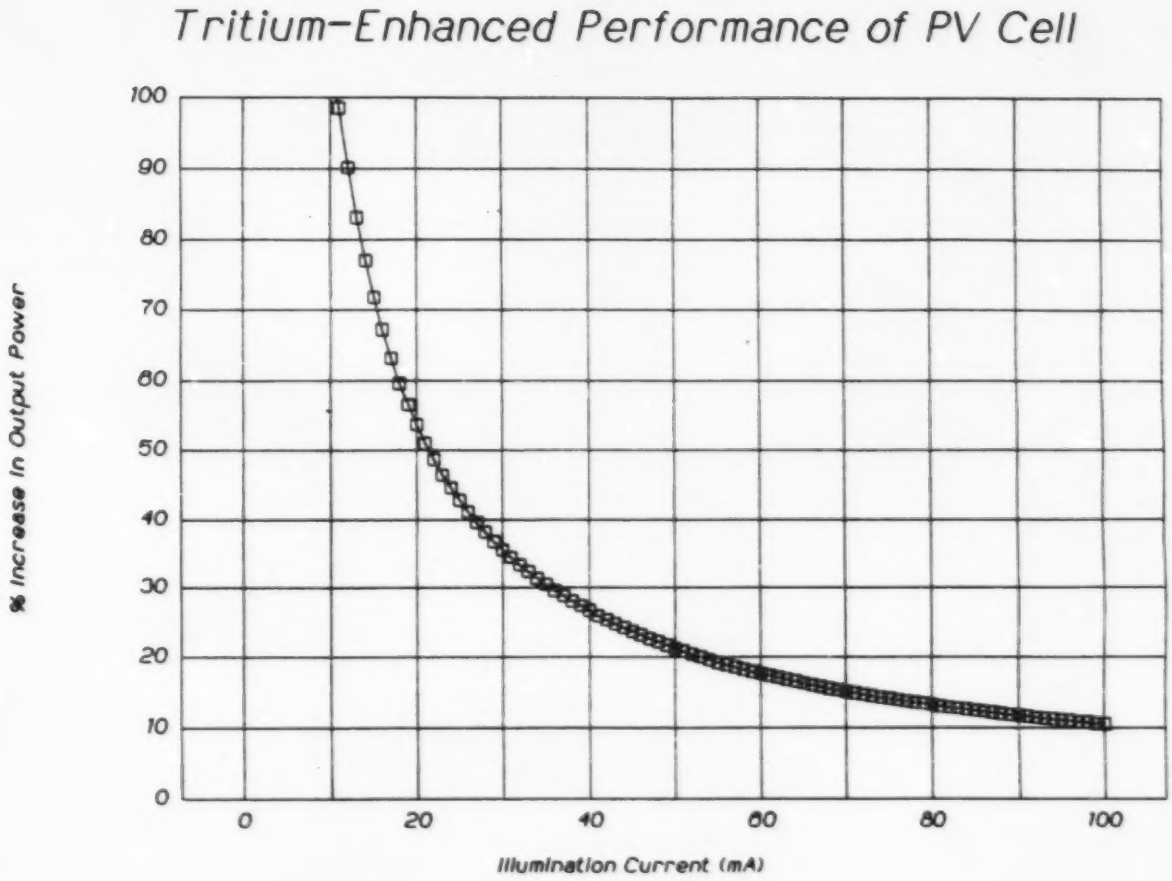

Figure 1. Results for theoretical calculations of the influence of tritium beta radiation on PV cell performance (output power), for a PV cell illuminated under various photon fluxes.

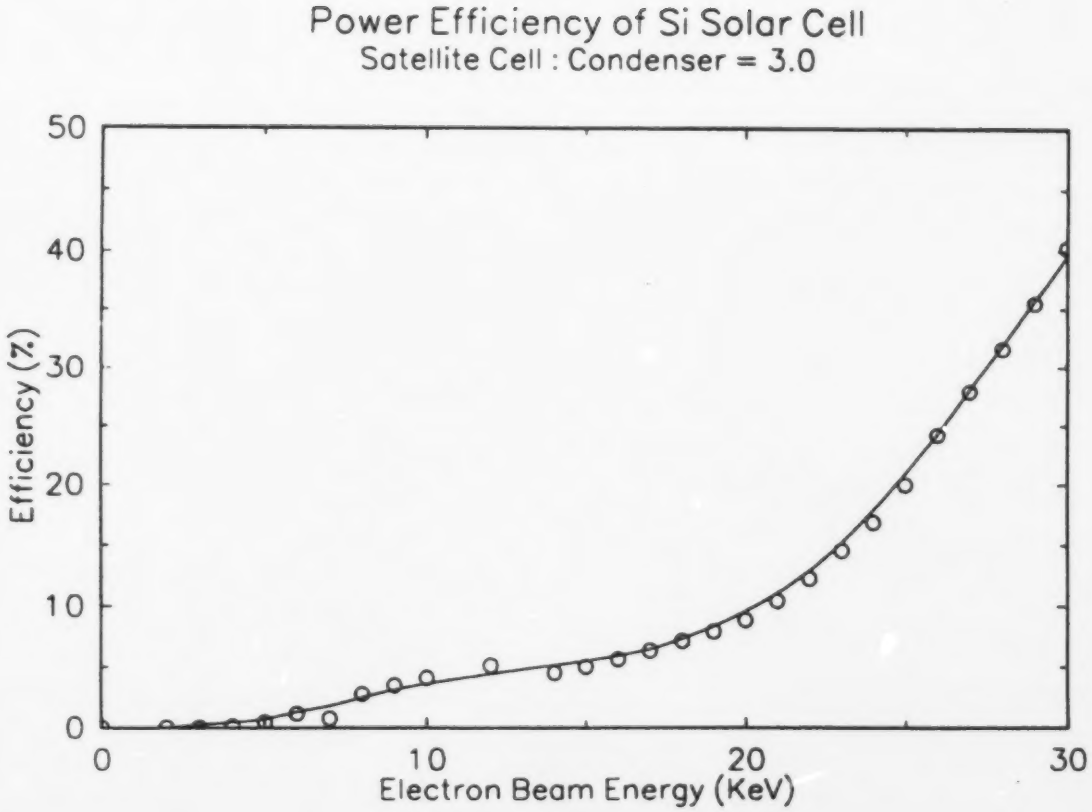

Figure 2. Power efficiency of unilluminated Si solar cell over the range of incident electron energies from 0 to 30 KeV.

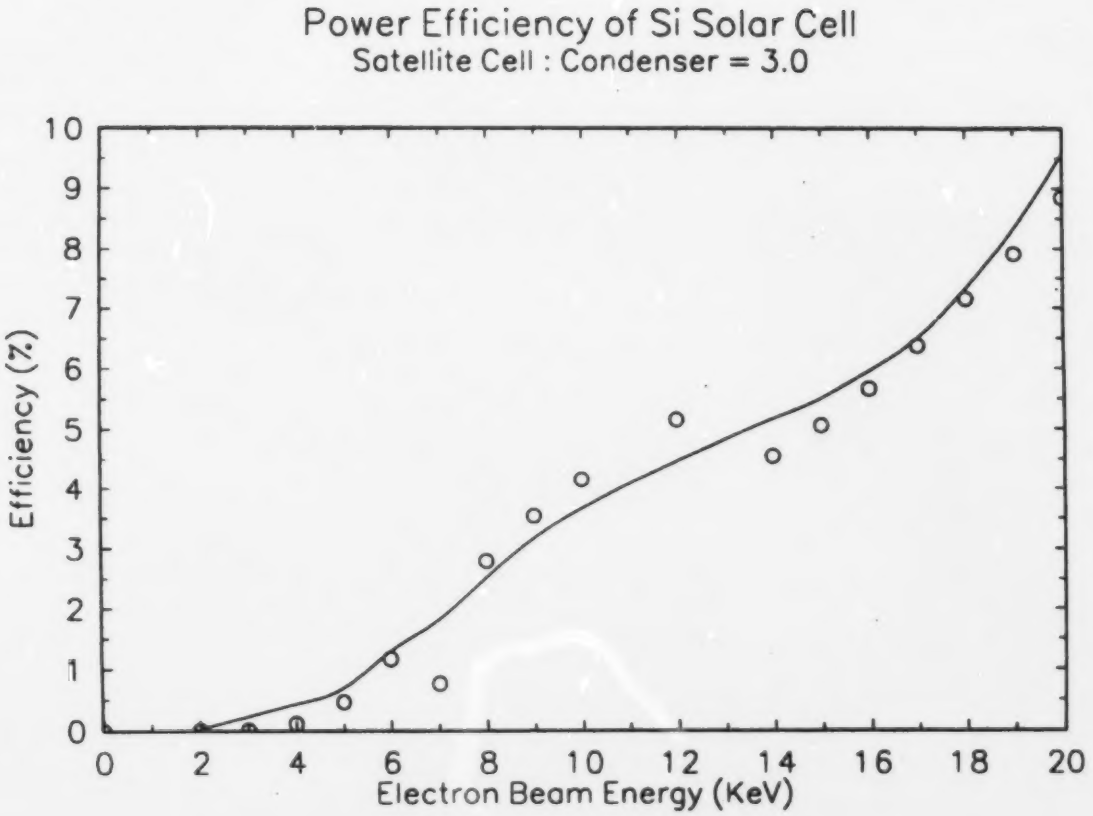

Figure 3. Detail of power efficiency curve of unilluminated Si solar cell over the range of incident electron energies from 0 to 20 KeV, the pertinent energy range for tritium beta radiation.